

P-25: Subatomic Physics

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Introduction

The Subatomic Physics Group (P-25) is engaged primarily in fundamental nuclear- and particle-physics research. Our objective is to conduct diverse experiments that probe aspects of subatomic reactions, in order to provide a more thorough understanding of the basic building blocks that make up our universe. Although our main focus is basic research, we also have a strong effort in applied programs such as proton radiography. To conduct our research, we often participate in large-scale collaborations that involve physicists from universities and institutions around the world, and we participate in or lead experiments at a variety of facilities. Currently, we are conducting research and developing new programs at Los Alamos National Laboratory and other laboratories, including Brookhaven National Laboratory (Brookhaven) and Fermi National Accelerator Laboratory (Fermilab). The following sections highlight the significant experiments and activities that we are currently pursuing.

The PHENIX Program at RHIC

P-25 has been exploring the subatomic physics that defined the universe at its beginning. Big Bang cosmology pictures a time very early in the evolution of the universe when the density of quarks and gluons was so large that they existed as a plasma, not confined in the hadrons we know today (neutrons, protons, pions, and related particles) (see Figure 1). As operations are commencing at Brookhaven's Relativistic Heavy-Ion Collider (RHIC), the effort has begun to produce a small sample of this primordial quark-gluon plasma in the laboratory and to study its exotic properties. The challenge facing the international collaborators involved in the RHIC program is to identify the fleeting transition into this deconfined phase of matter.

Physics Division has a long tradition of experiments at the high energy-density frontier, and P-25 is playing a major role in defining the search for the quark-gluon plasma and the related physics program for RHIC. To meet these goals, P-25 is playing a key role in constructing two major subsystems for the PHENIX (Pioneering High-Energy Nuclear Interaction eXperiment) detector, one of two major collider detectors at the RHIC facility. The PHENIX

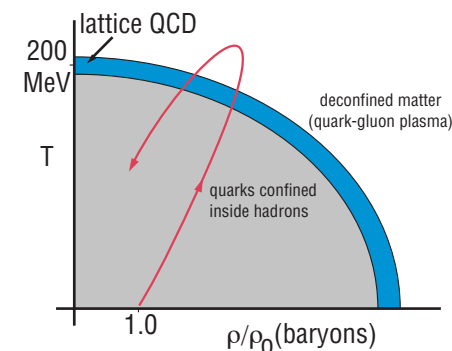


Figure 1. Lattice QCD calculations predict that at higher temperatures and densities, there will be a transition of matter from the confined state to the deconfined state, as shown by the solid band. Research with RHIC will explore this transition of matter.

collaboration currently consists of over 300 physicists and engineers from universities and laboratories in the U.S. and 14 foreign countries. Our work focuses on the multiplicity/vertex detector (MVD) and the muon subsystem. The MVD is the smallest and among the most technically complex of the PHENIX systems. It will surround the region where the two beams of 100-GeV/nucleon ions intersect. The functions of the MVD are to determine the precise location of the interaction vertex and to measure the global distribution and the total number of secondary charged particles; these properties

are crucial parameters in fixing the energy density achieved in the collision fireball. A partially instrumented MVD has taken highly preliminary data during the first physics run of the PHENIX.

The muon detectors, the largest subsystem in PHENIX, consist of two sets of position-sensitive tracking chambers surrounding conical magnets at opposite ends of the detector. Muons are identified by recording their penetration into a series of large steel plates interspersed with detection planes, all of which lie behind the magnets. The muon subsystem plays a central role in P-25's physics agenda because it is optimized for examining hard-scattering observables at very high temperatures and densities, where the strong force is smaller and easier to calculate using perturbative quantum chromodynamics (QCD). The first detector, known as the South Arm, is complete and is being moved into the interaction region for data taking in 2001. The North Arm is under construction; its completion date will depend on the availability of funds and periods for installation. (More details on this experiment are available in the research highlight "The PHENIX Detector Program at RHIC" in Chapter 2.)

High-Energy Nuclear Physics

Another area of study in P-25 is parton distribution in nucleons and nuclei, and the nuclear modification of QCD processes such as production of J/ψ particles (made up of a pair of charm/anticharm quarks). We are currently publishing research on this topic from a program centered at Fermilab. This program began in 1987 with measurements of the Drell-Yan process in fixed-target proton-nucleus collisions. Those measurements showed that the antiquark sea of the nucleon is largely unchanged in a heavy nucleus. In our most recent measurements during the NuSea Experiment (E866), we demonstrated a large asymmetry between down and up antiquarks, presumably due to the nucleon's pion cloud (see Figure 3). In addition we showed that the production of heavy vector mesons such as the J/ψ is strongly suppressed in heavy nuclei. We mapped out this effect over a broad range of J/ψ energies and angles. Although the causes of this suppression are not yet fully understood, it is already clear that absorption in the final state plays an important role, as do energy-loss of the partons and shadowing of

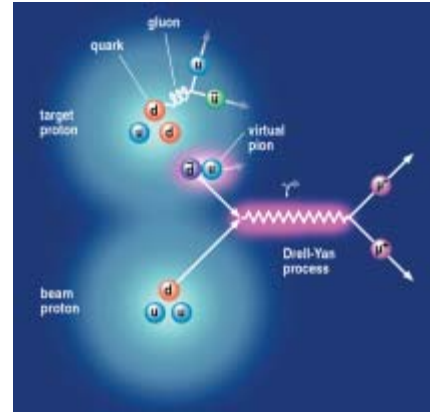


Figure 2. A proton consists of three valence quarks held together by gluons in a sea of quark-antiquark pairs. These pairs may be produced by gluon splitting, a symmetric process generating nearly equal numbers of anti-down, \bar{d} , and anti-up, \bar{u} , quarks, or from virtual-pion production, an asymmetric process that generates an excess of \bar{d} . We can determine \bar{d}/\bar{u} by measuring the properties of the muon pairs produced in the Drell-Yan process, which occurs when a quark in a proton beam strikes a sea antiquark in a target.

the gluon distributions. The muon arms at PHENIX are well poised to continue these studies when protons are collided with heavy ions at RHIC.

Spin Physics at RHIC

The muon detectors at PHENIX are also designed to study which components of the proton carry its spin. When both beams at the RHIC collider are composed of polarized protons, the proton-proton interactions will be directly sensitive to the fraction of spin carried by the gluons (see Figure 2). Previous measurements of deep inelastic scattering have only been sensitive to the sum of the quark and antiquark contributions to the spin, but the availability of polarized protons to induce the Drell-Yan process allows the separation of these two components by measuring the antiquark piece alone. Additionally, by measuring the asymmetry of the charge states of the intermediate vector boson (W), the flavor dependence (*i.e.*, the difference between up and down quark contributions) can be extracted. Spin physics is expected to commence at RHIC after a year or two of heavy-ion experimentation.

Liquid Scintillator Neutrino Detector

P-25 conducts experiments to explore neutrino oscillation, a phenomenon that has great implications in our understanding of the composition of the universe. The Liquid Scintillator Neutrino Detector (LSND) experiment at the Los Alamos Neutron Science Center (LANSCE) has provided evidence for neutrino oscillations, revealing an excess of oscillation events in both the muon-antineutrino to electron-antineutrino ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) and muon-neutrino to electron-neutrino ($\nu_\mu \rightarrow \nu_e$) appearance channels. These two channels are independent of each other and together provide strong evidence for neutrino oscillations in the $\Delta(m^2) > 0.2 \text{ eV}^2$ region. The LSND results imply that at least one of the neutrino types in each of these appearance channels has a mass greater than 0.4 eV. When combined with estimates of the number of neutrinos present in the universe, the LSND results suggest that neutrinos contribute more than 1% to the mass density of the universe. The existence of neutrino oscillations has great significance for nuclear and particle physics as well because it implies that lepton number is not conserved and that there is mixing among the lepton

families; these observations require extensions to the standard models. The LSND experiment, which had its last run in 1998, has also made precision measurements of neutrino-carbon and neutrino-electron scattering, which provide interesting tests of the weak interaction.

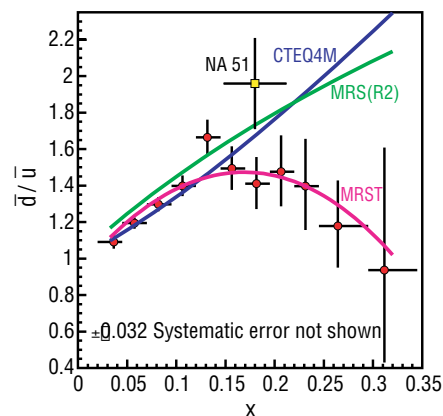


Figure 3. The ratio of \bar{d} to \bar{u} in the proton from the FNAL E866 NuSea as a function of the fraction of the proton's momentum carried by the quark x . NA51 was the only previous measurement of this quantity. The curves represent various parameterizations of \bar{d}/\bar{u} . The curve that best matches that data, labeled "MRST," was proposed only after the FNAL E866.

Booster Neutrino Experiment

The importance of the LSND results demands a definitive experiment to verify the results, and P-25 has been pursuing the Booster Neutrino Experiment (BooNE) to that end. This experiment will be conducted at Fermilab. The BooNE detector will consist of a 12-m-diameter sphere filled with 770 tons of mineral oil and covered on the inside by 1,280 photomultiplier tubes mostly recycled from the LSND experiment (see Figure 3). The detector will be located 500 m away from the neutrino source, Fermilab's 8-GeV proton booster and new neutrino-production horn. The proton booster will run nearly continuously, and if the LSND results are indeed due to neutrino oscillations, BooNE will observe approximately 1,000 $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation events after one year of operation. Furthermore, assuming oscillations are confirmed, BooNE will make precision measurements of the oscillation parameters and test for charge-conjugation parity violation in the lepton sector. The

contractors have given the collaboration beneficial occupancy of the detector tank and electronics rooms at Fermilab. The BooNE detector should be operational by the end of calendar year 2001, and first results are expected two years later.

MEGA

The apparent conservation of muon number remains a central problem of weak interaction physics. Most extensions to the standard models require a much larger mixing than would be predicted by neutrino oscillations. The search for such effects has been a research topic in P-25. Experimental evidence to date shows that muon decays always contain at least one electron and two neutrinos. However, the particle physics community believes in the need to extend the minimal standard model of weak interactions. Searches for decays that violate muon number conservation address these extensions. MEGA was an experimental program designed to make such a search at the Los Alamos Meson Physics Facility (LAMPF, now known as LANSCE). MEGA, which searched for muon decays yielding an electron and a gamma ray (hence, the acronym), completed its data collection in 1995. The extraction of kinematic properties for all of the muon decay events that potentially meet the MEGA criteria is now complete. (Please see the research highlight

“New Limit for the Lepton-Family Number Nonconserving Decay $\mu^+ \rightarrow e^+ \gamma$ in Chapter 2.) The combined data from the summers of 1993–1995 have not observed any events of the new type without neutrinos. This result improves the current world sensitivity to this process by a factor of 4 to 1.2×10^{-11} (branching ratio with 90% confidence).

Ultracold Neutrons

P-25 is collaborating with the Neutron Science and Technology Group (P-23) in experiments to provide better sources of ultracold neutrons (UCNs), neutrons that can be trapped by ordinary materials. Solid deuterium has been proposed for some time as a material to convert cold neutrons into UCNs. Recently, experiments conducted by Physics Division have demonstrated that coupling a solid deuterium moderator to a high intensity of cold neutrons can produce world-record densities of UCNs (see Figure 4). Using cold neutrons produced in the interaction of 800-MeV protons with tungsten, UCNs have been bottled with a factor of two higher neutron density than reactor-driven sources such as the Institute Laue-Langevin source, the previous record holder. The source of the protons was the LANSCE accelerator at Los Alamos.

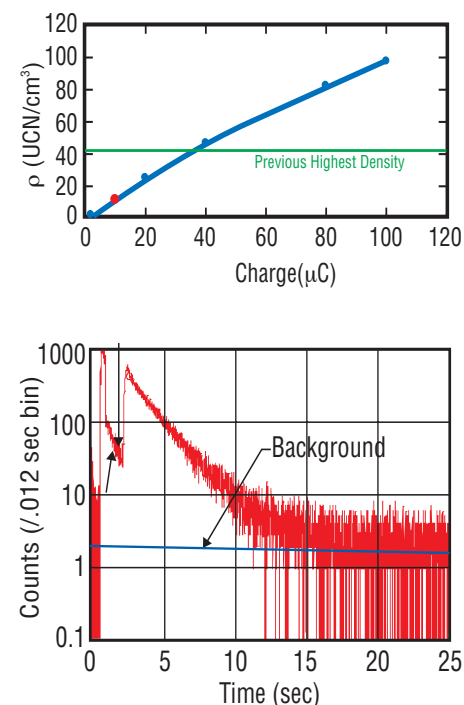


Figure 4. On June 29, 2000, we tested the prototype UCN source with beam intensities similar to those we would use for the full-scale source. The result was the highest density ever achieved of UCNs stored in a bottle, a factor of 2.5 greater than the world's previous highest density. The top plot shows the density achieved as a function of incident proton charge. The bottom plot shows the time structure of the detected UCNs, after the start of the proton pulse at time zero. The UCNs were stored for 1/2 second. About 30,000 UCNs were detected in the run shown, which corresponded to an incident charge of 100 μC of protons and a UCN density of

Electric Dipole Moment of the Neutron

P-25 is also participating with P-23 in a Laboratory project aimed at improving the limit on the electric dipole moment (EDM) of the neutron. Our interest in this topic is driven by the observation of violation of time-reversal invariance in the neutral kaon (K^0) system. Many theories have been developed to explain this time-reversal-invariance violation, but most have been ruled out because they predict a sizable EDM for the neutron, which experiments have yet to verify. Today, new classes of highly popular models, such as supersymmetry, predict EDM values that are potentially within the reach of experiment. In addition, if the observed baryon-antibaryon composition of the universe is due to time-reversal-violating symmetry breaking at the electroweak scale, the range of predicted EDM values is also measurable. We are currently working towards experimentally verifying the feasibility of conducting an experiment that should improve the limit on the neutron EDM by two orders of magnitude to 4×10^{-28} e·cm. A first test experiment has been completed at the Manuel Lujan Center to study the properties of

dilute mixtures of helium-3 in superfluid helium-4. Preliminary results from neutron tomography (see Figure 5) indicated that these properties are well suited to the planned experiment.

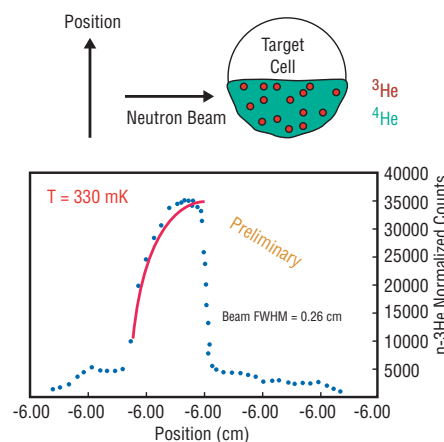


Figure 5. The upper part of the diagram illustrates the idea of neutron tomography. A highly collimated beam of neutrons is incident on a cylindrical cell filled with a small amount of helium-3 in superfluid helium-4. A neutron may absorb on the helium-3, and the reaction products produce light that can be observed and whose intensity is proportional to the amount of helium-3 in the path of the beam. By moving the cell across the beam, experimenters can deduce the distribution of helium-3. The lower part is the results of such a scan when the cell is half full. The sharp edge at the liquid boundary can be interpreted in terms of the size of the beam. The red line represent a purely geometric expectation but neglect many optical effects that will be included in the analysis.

Hypernuclei Physics

One of our recent interests has been the study of lambda (λ)-hypernuclei, where the λ replaces neutrons within nuclei. This substitution explores the strong interaction (the force that holds the nucleus of an atom together). In 1994, we proposed experiment 907 (E907) at Brookhaven's Alternating-Gradient Synchrotron (AGS) to study the reaction: nucleus plus negative kaon transforms into hypernucleus plus neutral pion. This method of production is a novel tool for producing λ -hypernuclei with significantly better energy resolutions than those produced in the previous experiments. Additionally, E907 was capable of measuring the π^0 weak-decay modes of λ -hypernuclei that have never been studied previously. The LANSCE neutral meson spectrometer and associated

equipment were moved to the AGS for this experiment. A new data-acquisition system and a new array of active target chambers were successfully installed. We have published the first hypernuclear spectrum using the (K^-, π^0) reaction, and it has a resolution (2 MeV) that is roughly a factor of two better than any previous measurement. In addition, the π^0 energy spectrum that results from the weak-decay of light λ -hypernuclei has also been measured and is under analysis.

Theory

In addition to the fundamental experiments conducted in our group, P-25 has a strong theory component, which consists of a staff member, a postdoctoral fellow, and a number of short- and medium-term visitors from universities and laboratories throughout the world. Theoretical research focuses on basic issues of strong-, electromagnetic-, and weak-interactions topics that complement the present activity of the experimental program and that impact possible future scientific directions in the group. As such, our theoretical team facilitates interaction between experimental and theoretical activities in the nuclear and particle physics community and contributes to a balanced scientific atmosphere within the group. Recent theoretical activity has focused on parity violation in chaotic nuclei, deep inelastic and Drell-Yan reactions on nucleons and nuclei, QCD at finite temperatures, and the EDM of the neutron.

Proton Radiography

P-25 has a very strong applied program in proton radiography (P-RAD). The P-RAD program has three goals. The first is to demonstrate that high-energy proton radiography is a suitable technology for meeting the goals established for the advanced radiography program, the second is to advance the technology, and the third is to apply 800-MeV proton to the needs of science-based stockpile stewardship (SBSS) program. These goals are highly coupled because many of the techniques developed for 800-MeV radiography can be used at higher energies. In the last year alone, we have carried out 28 successful shots that address a wide range of SBSS issues. Additionally, we have moved beyond a successful demonstration of P-RAD at 25-GeV using the AGS at Brookhaven and have begun experiments relevant to the stockpile at this energy. Our successes and experience are being transferred to the designers of the Advanced Hydrotest Facility (see Figure 6). For more information on our P-RAD efforts, refer to the research highlight “Proton Radiography” on this topic in Chapter 2.

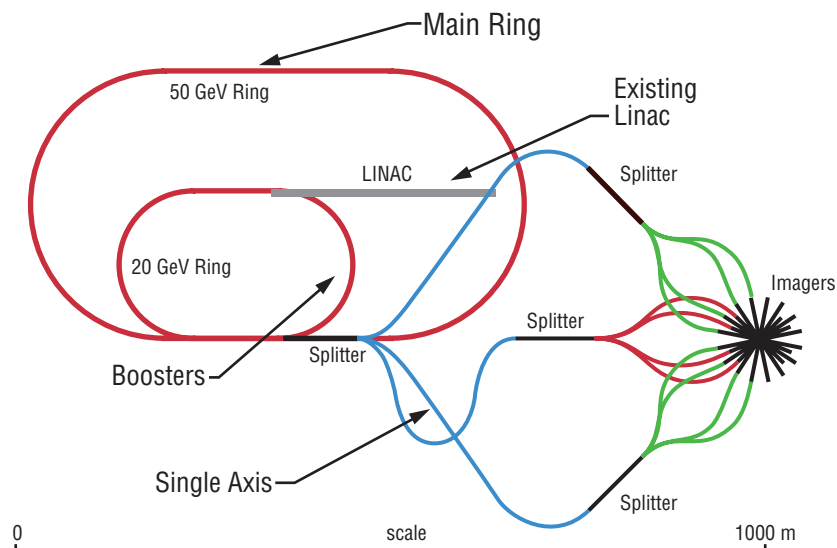


Figure 6. Concept of the P-RAD Advanced Hydrotest Facility (AHF). PRISM, a subset of the AHF, would include the linac injector, the main 50-GeV acceleration ring, a single-axis extracted beam line, a firing point, and a lens system.

Quantum Computation using Cold, Trapped Ions

In another applied program, P-25 is collaborating with P-23 to develop quantum-computation technology. Quantum computation is a new computational paradigm that is much more powerful than classical computation because it allows computing with quantum-mechanical superpositions of many numbers at once. In a quantum computer, binary numbers will be represented by quantum-mechanical states (“qubits”). We are developing a quantum-computational device in which the qubits will be two electronic states of calcium ions that have been cooled with a laser to rest in an ion trap. Once these ions are resting in the trap, we will perform quantum logical operations with a laser beam that is resonant with the qubit transition frequency and is directed at individual ions. We have constructed diode laser systems for the 866-nm and 854-nm calcium ion transitions and a frequency doubler for an amplified 794-nm laser diode. These lasers are locked to an optical transfer cavity to provide continuous, independent

tuning with laser stability of 1 MHz. We have designed and built an ultra-stable 729-nm laser capable of resolving motional sidebands of trapped calcium ions, and we have trapped and imaged clouds of ions frozen into strings. Spectra of the 729-nm calcium transition have been studied in preparation for sideband cooling designed to put the ions in their motional ground state.

Education and Outreach

P-25 group members continue to be active in education and outreach activities, both as participants in programs sponsored by the Laboratory and as individual citizens who volunteer their time for various activities. Recent group-member activities include acting as judges for the New Mexico Supercomputing Challenge, participating in career days and college days at New Mexico schools, and visiting classrooms. We also coordinated, organized, and participated in the Teacher’s Day at the annual meeting of the American Physical Society’s Division of Nuclear Physics.

In addition to these outreach activities, P-25 sponsors several high school, undergraduate, and graduate students to work on projects within the group. Through their individual schools, these students study physics, computing, engineering, and electromechanical technical support, and they supplement their learning through interaction with Laboratory mentors and real on-site experience. Several students are writing theses based on the work they do at P-25.

New Initiatives

Our group is constantly seeking new research opportunities to replace completed ones. At Fermilab, we are members of a collaboration that proposes to extend the range of measurement of the pion cloud feature of nucleons uncovered in with the Drell-Yan process. This effort is in the approval process. We have explored a role for P-25 within the energy upgrade/hall D addition at the Jefferson National Laboratory, and have made suggestions for both experiments and detectors to be used in that facility. Recently, the Japanese Hadron Facility was approved by their government. We have contributed to their ideas for utilizing it by submitting two letters of intent: one for Drell-Yan physics and one for neutrino-proton elastic scattering. Our staff has made a number of visits including two of two months as well as participating in their workshops. We are well poised to be involved if the opportunities continue to look promising. Finally, we have studied the advantages of relativistic electron-nucleus collisions at an eRHIC facility.

Further Information

All of the research described is aimed at increasing our understanding of subatomic reactions, and we are poised to make exciting discoveries in nuclear and particle physics over the next several years. To learn more about these projects, as well as the other work being conducted in our group, please see the project descriptions in Appendix A. Some of our major achievements are also covered as research highlights in Chapter 2. These include our work in high-energy nuclear physics, rare muon decays, and proton radiography.